

Longitudinal Single-Spin Asymmetries in Proton-Proton Scattering with a Hadronic Final State

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Abstract

We consider longitudinal, parity-violating single-spin asymmetries in proton-proton collisions at RHIC. The focus of this study is on the production of single-inclusive jets, as well as on jets that contain a charm quark. While the asymmetry for inclusive jets turns out to be small, we find considerably larger effects for the case of charm production. We also investigate the role of leading threshold logarithms and find that they increase the polarized and unpolarized cross sections and reduce the spin asymmetry.

1 Introduction

Over the past decades already much information on the nucleon's quark and anti-quark helicity distributions, Δq and $\Delta \bar{q}$, has been collected. The key processes exploited so far are inclusive and semi-inclusive deep-inelastic lepton nucleon scattering (DIS) (see Refs. [1, 2] for recent experimental work). Inclusive DIS only measures the combinations $\Delta q + \Delta \bar{q}$, while semi-inclusive DIS allows to separate the quark and anti-quark distributions, albeit with relatively large uncertainties associated with fragmentation. Entirely independent and complementary information on the Δq and $\Delta \bar{q}$ will be obtained from the study of parity-violating single-spin asymmetries (SSAs) in proton-proton scattering at RHIC [3, 4, 5].

The main focus of the measurements of parity-violating spin asymmetries planned at RHIC is on the production of W -bosons and their subsequent decay into a charged lepton and the corresponding unobserved (anti-)neutrino. This process can lead to large longitudinal SSAs, of the order of 50 %. Moreover, the process is “clean” in the sense that only the single generic subprocess $q\bar{q}' \rightarrow W \rightarrow l\nu$ contributes to lowest perturbative order (LO), which in principle allows a direct study of a particular quark or anti-quark helicity distribution [3, 4, 5]. Also, as the final state is generated by the electroweak interaction, QCD radiative corrections to the process are relatively simple to calculate and well understood [6]. On the other hand, the counting rates for lepton final states are low.

In the present note, we discuss parity-violating SSAs with a hadronic final state, such as a jet at large transverse momentum p_T . This potentially provides an interesting alternative to the leptonic signal, foremost because jets are produced much more copiously than leptons. The idea to use parity-violating SSAs to see hadronic W decays [7] actually predates the discovery of the W s. The specific application to RHIC with the aim of obtaining information on the spin-dependent quark

and anti-quark distributions was discussed in [8], where also the results for all the associated LO subprocess cross sections were presented. First-order QCD corrections were computed in Ref. [9], and turn out to be quite significant. Apart from updating the expectations for the LO parity-violating SSA by using a more recent set of polarized parton distributions, we extend the theoretical status of higher-order QCD corrections by taking into account the resummation of large leading threshold logarithms to the cross sections. We also discuss the special case of jets that contain a charm quark. We find that in this case a much more favorable SSA is obtained than for the single-inclusive jet case.

2 Parity-violating longitudinal SSAs for single jet production

A non-vanishing longitudinal SSA in the process $\vec{p} + p \rightarrow \text{jet} + X$ is parity-violating and can only arise through participation of the weak interactions. Here we consider this reaction at the lowest order of perturbation theory. All the involved partonic cross sections for the process have been known for a long time [8]. We have confirmed the corresponding results. There are five different helicity structures for these cross sections,

$$\begin{aligned} (1) & (1 - \lambda_1 \lambda_2) & (2) & (1 + \lambda_1 \lambda_2) \\ (3) & (1 - \lambda_1)(1 - \lambda_2) & (4) & (1 + \lambda_1)(1 + \lambda_2) & (5) & (1 - \lambda_1)(1 + \lambda_2), \end{aligned}$$

where λ_1 and λ_2 denote the helicities of the partons in the initial state. All these structures contribute to the spin-averaged pp cross section, $\sigma_{\text{unp}} = (\sigma_{++} + \sigma_{+-} + \sigma_{-+} + \sigma_{--})/4$, while the parity-conserving structures (1) and (2) drop out in the polarized cross section, which we define according to $\sigma_{\text{pol}} = (\sigma_{++} + \sigma_{+-} - \sigma_{-+} - \sigma_{--})/4$, the subscripts denoting the proton helicities. Note that this definition implies that the helicities of the “second” proton are summed over, so that we are considering a $\vec{p}p$ collision, and we can also write $\sigma_{\text{pol}} = (\sigma_+ - \sigma_-)/2$, where the helicities refer to the polarized proton. Also note that in the following the rapidity of a produced final-state particle will be counted positive in the forward direction of the “first” (the polarized) proton.

In terms of coupling constants, three different types of processes are taken into account. First, the $\mathcal{O}(\alpha_S^2)$ pure QCD (2-parton) \rightarrow (2-parton) processes. Because these do not violate parity, they only contribute to the unpolarized cross section. Second, partonic processes of $\mathcal{O}(\alpha_S \alpha_W)$, i.e., interference terms between strong and electroweak amplitudes. These generate a non-vanishing SSA [8]. The interference with the strong interaction generally leads to larger counting rates for the polarized cross section, compared to a reaction with a leptonic final state. Finally, there are purely electroweak partonic processes of $\mathcal{O}(\alpha_W^2)$. While these are of lesser importance for the asymmetry for jet production, they dominate in the case of charm production, as we will discuss below. All in all, the asymmetry is schematically of the form $[\mathcal{O}(\alpha_S \alpha_W) + \mathcal{O}(\alpha_W^2)] / [\mathcal{O}(\alpha_S^2) + \mathcal{O}(\alpha_S \alpha_W) + \mathcal{O}(\alpha_W^2)]$. Regardless of the fact that the various terms have mixed perturbative orders in α_S and α_W , we collectively refer to them as “leading order”, since they all contribute at $2 \rightarrow 2$ tree level.

The spin-averaged hadronic jet production cross section is given by

$$\frac{d\sigma_{\text{unp}}}{dp_T d\eta} = \sum_{a,b} \frac{1}{1 + \delta_{ab}} \int_{x_{\min}}^1 dx_1 \frac{2p_T}{x_1 - \frac{p_T}{\sqrt{s}} e^\eta} \left[x_1 f^{a/p}(x_1, \mu^2) x_2 f^{b/p}(x_2, \mu^2) \frac{d\hat{\sigma}_{ab,\text{unp}}}{d\hat{t}} + (a \leftrightarrow b) \right], \quad (1)$$

where p_T and η are the jet’s transverse momentum and pseudo-rapidity, respectively, and where $x_{\min} = x_T e^\eta / (2 - x_T e^{-\eta})$, $x_2 = x_1 x_T e^{-\eta} / (2x_1 - x_T e^\eta)$ with $x_T = 2p_T / \sqrt{s}$. The $d\hat{\sigma}_{ab,\text{unp}}/d\hat{t}$ with $\hat{t} = (p_a - p_{\text{jet}})^2$ are the spin-averaged $2 \rightarrow 2$ partonic cross sections, and the $f^{a,b/p}$ the distributions for partons a, b in the proton. To compute σ_{pol} one just has to use the appropriate polarized partonic cross sections in Eq. (1), and to replace the distribution $f^{a/p}$ by the corresponding

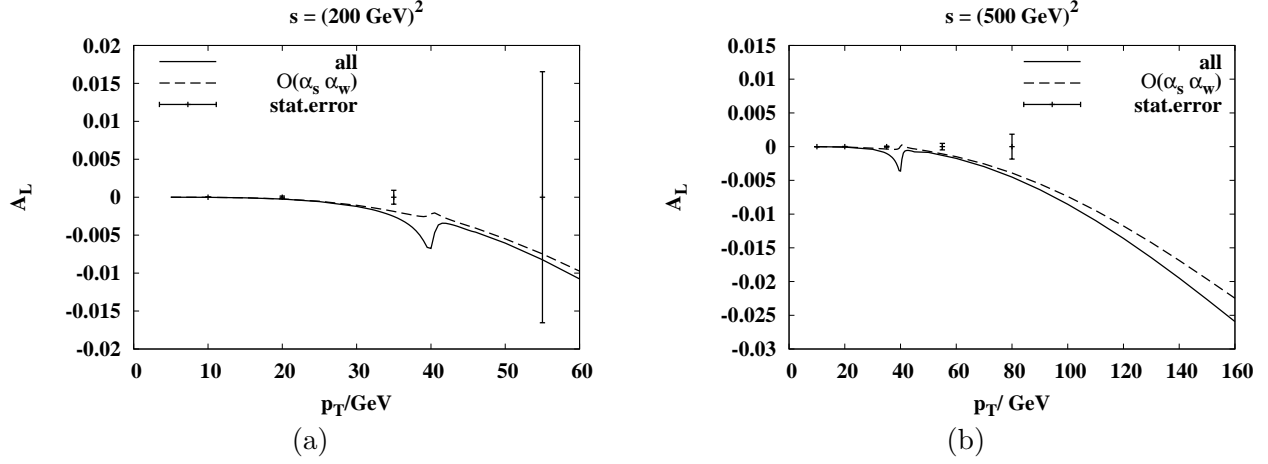


Figure 1: The single-spin asymmetry A_L for single-inclusive jet production, for the two RHIC energies. Dashed lines: contributions of $\mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_s \alpha_w)$; solid lines: including also the contributions of $\mathcal{O}(\alpha_W^2)$. The indicated statistical error projections are estimated assuming an integrated luminosity of 100 pb^{-1} for $\sqrt{s} = 200 \text{ GeV}$ and of 500 pb^{-1} for $\sqrt{s} = 500 \text{ GeV}$, as well as a beam polarization of 70%.

helicity distribution $\Delta f^{a/p}$. In our numerical calculations we use the parton distribution functions of [10, 11]. We choose $\mu = p_T$ for the scale of the parton densities and of the strong coupling constant.

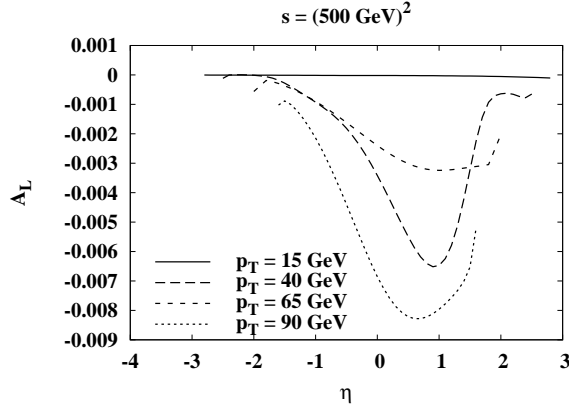


Figure 2: A_L for jet production at $\sqrt{s} = 500 \text{ GeV}$ as a function of η for different values of p_T .

where the (resonant) s -channel production of weak gauge bosons becomes large. In Fig. 1 we have also displayed the statistical errors to be expected for integrated luminosity $\mathcal{L} = 100 \text{ pb}^{-1}$ for $\sqrt{s} = 200 \text{ GeV}$ and $\mathcal{L} = 500 \text{ pb}^{-1}$ for $\sqrt{s} = 500 \text{ GeV}$, as well as a beam polarization $P = 70 \%$. These have been estimated as $\delta A_L = 1/(P\sqrt{\mathcal{L} \cdot \sigma_{\text{unp}}})$, where σ_{unp} has been integrated over the following p_T -bins: (5-15), (15-25), (25-45), (45-65), (65-95) GeV. Even though the asymmetry is very small, it may nevertheless be measurable at $\sqrt{s} = 500 \text{ GeV}$, at high p_T .

Figure 2 shows A_L for several fixed p_T values as a function of η . $|A_L|$ becomes maximal at posi-

Figure 1 shows the spin asymmetry $A_L = \sigma_{\text{pol}}/\sigma_{\text{unp}}$ for two different center-of-mass (c.m.) energies, $\sqrt{s} = 200 \text{ GeV}$, the present RHIC energy, and $\sqrt{s} = 500 \text{ GeV}$, the energy that will be used for the W physics program. We present A_L as a function of p_T , integrated over $-1 < \eta < 1$. For the solid lines in Fig. 1 all partonic contributions have been included, while for the dashed lines the purely electroweak contributions of $\mathcal{O}(\alpha_W^2)$ have been excluded. A_L increases with p_T , but it remains overall rather small. This is due to the large QCD contribution in the denominator of the asymmetry, which has gluon-induced contributions and also the larger (and positive-definite) partonic cross sections. Purely electroweak contributions are only important starting from $p_T \simeq 30 - 40 \text{ GeV}$,

tive η when a large- x quark from the polarized proton participates in the scattering. The plot shows that by integrating over a suitable η -range one may optimize between magnitude of the asymmetry on the one hand and the size of the statistical error bars on the other. Measurements at large positive η might give valuable information on the helicity distributions at large x , complementary to that obtained in lepton nucleon scattering.

3 Resummation of leading threshold logarithms

Near the partonic threshold, $\hat{x}_T = 2p_T/\sqrt{\hat{s}} \sim 1$, when the initial partons have just enough energy to produce the high- p_T jet and an unobserved recoiling partonic final state, large logarithmic corrections of the form $\alpha_S^k \ln^m(1 - \hat{x}_T^2)$ with $m \leq 2k$ arise at the k th order of perturbation theory. These result from the emission of soft and collinear gluons. If the threshold region plays a significant role for the hadronic cross section, which is the case for RHIC when the jet transverse momentum becomes large, the logarithmic corrections need to be resummed to all orders in α_S , at least for the leading towers of logarithms, in order to maintain a useful perturbative expansion. The resummation is usually performed in Mellin- N moment space, with moments taken in x_T^2 . To leading double logarithmic (LL) accuracy ($m = 2k$), which we will focus on in the present study, the resummed cross section is for each partonic subprocess given by [12]

$$\hat{\sigma}_{ab}^{(\text{res})}(N) = \sum_{c,d} \Delta_N^a \Delta_N^b J_N^d \hat{\sigma}_{ab \rightarrow cd}^{(\text{Born})}(N), \quad (2)$$

where $\hat{\sigma}_{ab \rightarrow cd}^{(\text{Born})}(N)$ are the moments of the Born cross sections. Here, parton c is the “observed” final-state parton that produces the jet. $\Delta_N^{a,b}$ and J_N^d are “radiative factors” associated with gluon emission from the external legs a, b, d of the Born process. They contain all leading logarithms. As was discussed in [12], emission off parton c does not produce double logarithms. For details and the precise definition of the various factors in Eq. (2), see [12] and the references therein.

Eq. (2) as written applies to the cross section integrated over all η , which takes the form of a genuine mathematical convolution of parton distributions and partonic cross sections. The Mellin moments of the hadronic cross section in x_T^2 can be computed from this as $\sigma(N) = \sum_{a,b} \hat{\sigma}_{ab}^{(\text{res})}(N) f^{a/p}(N) f^{b/p}(N)$, where $f^{a/p}(N), f^{b/p}(N)$ are the Mellin moments of the parton densities. The hadronic cross section as a function of p_T would then be obtained by applying an inverse Mellin transformation. However, in the LL approximation, one can follow a somewhat simpler procedure. We can absorb the resummation effects into the parton distribution functions in moment space, multiplying for example $f^{a/p}(N)$ by the associated radiative factor Δ_N^a , and likewise for parton b . One next also includes the factor J_N^d appropriately. To give a specific example, let us consider the subprocess $qq \rightarrow qq$. We write the resummed cross section as

$$\hat{\sigma}_{qq}^{(\text{res})}(N) = \underbrace{[f^{q/p}(N) \Delta_N^q]}_{\rightarrow \tilde{f}^{q/p}(x_1)} \underbrace{[f^{q/p}(N) \Delta_N^q J_N^q]}_{\rightarrow \hat{f}^{q/p}(x_2)} \hat{\sigma}_{qq \rightarrow qq}^{(\text{Born})}. \quad (3)$$

We have introduced in this equation “pseudo”-parton distributions $\tilde{f}^{q/p}$ and $\hat{f}^{q/p}$ that incorporate the resummation effects. Use of these in the ordinary momentum-space LO cross sections of [8] will evidently give a result equivalent to the full LL resummation in Mellin space, but with the advantage that one does not need to compute the Mellin moments of the Born cross sections. Of course, for a general partonic process there is an ambiguity regarding whether one absorbs the factor $J_N^{q,g}$ into $f^{a/p}$ or $f^{b/p}$. To compensate for this, we simply symmetrize afterwards by using the combination $(\tilde{f}^{a/p}(x_1) \hat{f}^{b/p}(x_2) + \hat{f}^{a/p}(x_1) \tilde{f}^{b/p}(x_2))/2$. This plays no role if the cross section is integrated over

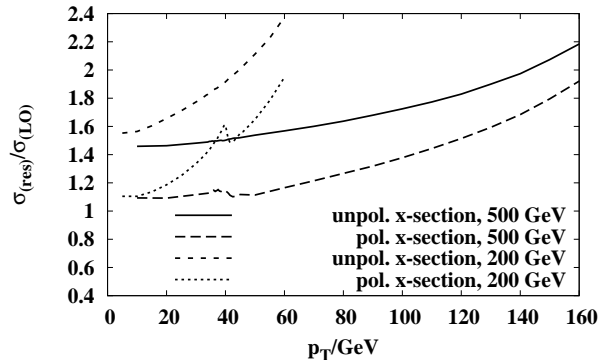


Figure 3: LL threshold resummation effects for single-inclusive jet production. The plots show the ratios $\sigma_{\text{unp}}^{(\text{res})}/\sigma_{\text{unp}}^{(\text{LO})}$ and $\sigma_{\text{pol}}^{(\text{res})}/\sigma_{\text{pol}}^{(\text{LO})}$ for two different c.m.-energies.

all η . If the integration over η is performed only over a limited (but large and symmetric) range, the above procedure is no longer exact, but should still give a good approximation to the expected LL resummation effects.

Figure 3 shows our results for the LL threshold resummation for the unpolarized and polarized cross sections. One can see that in general resummation increases the jet cross sections at RHIC, as expected [12]. It turns out that the unpolarized cross section is more affected by resummation than the polarized one. This is also expected since processes with gluon initial states, which typically receive the largest resummation effects due to the larger color charge of gluons, are absent in the polarized case at LO. As a result, resummation tends to further decrease the parity-violating asymmetry A_L , by roughly 30 %. This finding is qualitatively consistent with the results of the full NLO calculation of [9], even though more detailed studies are needed here.

4 Charm production

One can strongly reduce the large gluon-induced QCD background that suppresses A_L if one considers an SSA for the production of a charm quark, i.e., the process $\vec{p}+p \rightarrow c+X$. Since we take the charm quark to be at high transverse momentum, we can neglect its mass. In order to have a realistic calculation, one would need to include a fragmentation function for the charm quark turning into a charmed hadron. For our first exploratory study here, however, we neglect the fragmentation process. Ignoring intrinsic charm in the nucleon, only two of the pure-QCD channels survive for charm production, namely $q\bar{q} \rightarrow c\bar{c}$ and $g\bar{g} \rightarrow c\bar{c}$, leading to an enormously reduced unpolarized cross section in comparison to jet production. Unfortunately, however, also the contribution of $\mathcal{O}(\alpha_S\alpha_W)$ becomes much smaller. The only partonic subprocesses for this are $d\bar{d}, s\bar{s} \rightarrow c\bar{c}$, which are either CKM-suppressed or enter with the strange quark distribution. Therefore, the main contributions to σ_{pol} are of $\mathcal{O}(\alpha_W^2)$, as shown in Fig. 4, similar to the lepton decay channel. Nonetheless, one can see from the figure that the asymmetry A_L integrated over the charm's pseudo-rapidity $|\eta| \leq 1$ reaches up to about 15 % for $\sqrt{s} = 200$ GeV, and up to 10 % for $\sqrt{s} = 500$ GeV. The pronounced peaks at both energies are generated by s -channel production of the weak gauge bosons, most notably the W . The statistical errors of the asymmetry, which have been estimated under our earlier assumptions without including a charm detection efficiency, are reasonably small in the peak-region. In

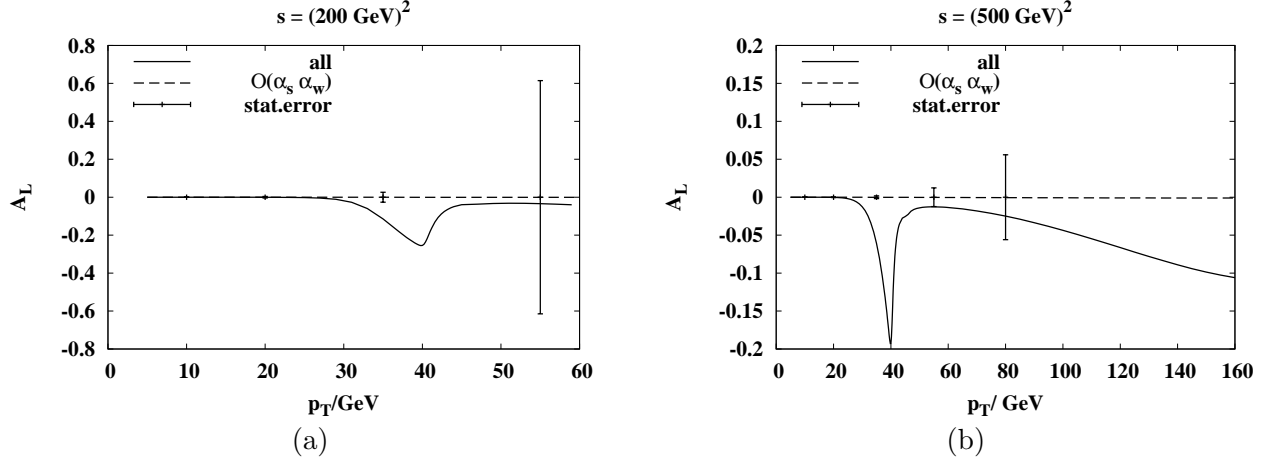


Figure 4: Single-spin asymmetry A_L at LO for charm production. Dashed lines: contributions of $\mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_s \alpha_W)$; solid lines: including also the contributions of $\mathcal{O}(\alpha_W^2)$. The indicated statistical error projections are estimated assuming an integrated luminosity of 100 pb^{-1} for $\sqrt{s} = 200$ GeV and of 500 pb^{-1} for $\sqrt{s} = 500$ GeV, as well as a beam polarization of 70%. They do not take into account a charm detection efficiency.

Fig. 5, A_L is shown as a function of η , for different values of p_T . The effects can become of the order of 50%, i.e., as large as in the case of the production of a lepton pair. Charm production probes in particular the large- x u -quark distribution in the proton, and the \bar{d} distribution at moderately low x .

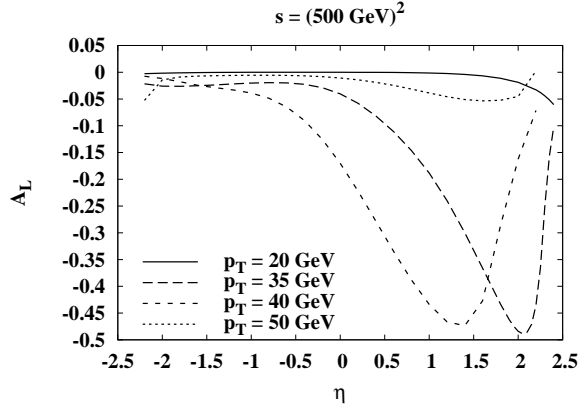


Figure 5: A_L for charm production at $\sqrt{s} = 500$ GeV as a function of η , for different values of p_T .

5 Summary and Conclusions

We have studied parity-violating single spin asymmetries in proton-proton scattering with hadronic final states for RHIC kinematics. In general, measuring such parity-violating observables can provide new, complementary information on the quark helicity distributions of the nucleon. Inclusive jets are produced copiously, but suffer from a very small spin asymmetry A_L (typically below 1%). Also, because of the many partonic channels that contribute to jets, the information on the polarized parton distributions from A_L for jets is not as clear-cut as for the usually considered lepton final state. Still, the jet A_L should be accessible at RHIC with the projected luminosity and might be a

tool for an early detection of a parity-violating signal. We have estimated the role of QCD higher-order effects by implementing leading-logarithm threshold resummation and found that the cross sections are increased by resummation, but that the asymmetry is decreased further. For a charm final state, rates are reduced, but the asymmetry can become much larger.

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